The Technological and Commercial Expansion of Electric Propulsion in the Past 24 Years

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Abstract: These instructions give you guidelines for preparing papers for IEPC17. Use this document as a template if you are using Microsoft Word 6.0 or later. Otherwise, use this document as an instruction set. Define all symbols used in the abstract. Do not cite references in the abstract. The footnote on the first page should list the job title and email address for each author.

I.Introduction

IN the hundred years since electric propulsion (EP) was originally conceived it has been developed by an increasing number of research and industrial entities worldwide1. To date a myriad of technological subclasses of EP exist[2,3], each at a different Technological Readiness Level (TRL), from basic notions of particle acceleration techniques to space proven applications.

During the first decades, following the first operation in space of an EP system in 1964, most development efforts have beeninvested in maturing five main types of EP technologies – ion engines, pulsed plasma thrusters (PPT), resistojets, arcjets, and Hall thrusters.

The principle drivers supporting the research, development, and ultimately qualification of each of the five technologies were government entities; either space agencies or different branches of the military. Most of the early missions were technology demonstrators and served purely scientific or technological purposes such as the Vela,

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Space Electric Rocket Test (SERT),', Zond, Lincoln Experimental Satellite (LES) or 'Meteor' missions[1,4]. With time, as EP technologies matured, new and improved propulsion systems were implemented to enable new satellite maneuverability and execute a variety of missions. The combination of mission requirements and commercial incentives resulted in EP technology being used principally in GEO communication and in Earth observation satellites. The lead players capable of developing and implementing EP technologies were the large geo-political entities, namely the United States, Soviet Union, Japan, Europe, and China.

The first truly operational uses of electric propulsion were for spacecraft attitude control on the Russian Zond-2 in 1964, which used pulsed plasma thrusters, and by the U.S. Vela satellites, which in 1965 used resistojets5. The first U.S. use of PPTs was on the U.S. LES and NOVA satellites6, which in 1968 started using pulsed plasma thrusters for fine ephemeris control to achieve a "drag-free" orbit. The first commercial use of electric propulsion was in 1981 with the launch of the Intelsat V series of GEO satellites, which used high power resistojets for NSSK, followed rapidly by their use on RCA's Satcom1 [citation]. Unfortunately, while the use of high power resistojets continues successfully to this day on the original Iridium constellation (77 spacecraft) and many geosynchronous satellites (over 20 to date), neither the use of PPTs nor resistojets precipitated a world-wide adoption of electric propulsion, likely due to the incremental nature of the performance improvement they provide. For this reason resistojets are not included in the statistics in this paper.

In parallel to the commercial use of resistojets, considerable research and development as well as several demonstration missions continued with the objective of increasing the capabilities and reducing the cost of space missions. It was acknowledged that the use of these propulsion devices would thrive with the commercialization of an increasing number of satellites7 due to the increased financial incentives in the commercial marketplace

Figure 1. Illustration of Telstar 401 - the first commercial satellite to use electric propulsion.

In 1993, 24 years ago, Martin Marietta's communications satellite Telstar 401 was launched and successfully operated using arcjet thrusters for GEO orbit north-south station-keeping8 (Figure 1). While not the first communications satellite to use EP for station-keeping, it marks the point in time when EP technology changed the commercial satellite marketplace and drove the broad, world-wide adoption of EP technology. The use of arcjets for NSSK also demonstrated the crucial link between the selection of in-space propulsion technology and launcher requirements: the mass reduction enabled by arcjets resulted in a significant reduction in launcher costs. The commercial success of the Telstar 401 mission removed major barriers preventing private and commercial satellite operators from harnessing EP technology.

Following Telstar 401 there was a rapid increase in the number of satellite integrators implementing EP-based propulsion systems on their satellite platforms. To compete with the strong advantages of arcjet technology the additional primes adopted other forms of electric propulsion, such as ion and Hall thrusters. Over time, EP technology has made great technological and commercial progress. The main driver for the impressive advancement is the slow and steady commercialization of the space industry led by a constant demand for an increasing number of communication satellites. In parallel, EP technology demonstrated the capability to perform a variety of functions and is increasingly used in almost all space applications, from tiny cubesats, through Earth observation satellites in LEO, to remote interplanetary missions9.

In this paper, we review the expansion process of EP in the last 24 years. To do so, we focus on four particular spacecraft niches: (1) communication satellites in GEO, (2) satellites in LEO, (3) interplanetary or deep space missions, and (4) small satellite platforms under 100 kg. For each niche, we present statistics showing the chronological increase in the number of satellites carrying EP devices. Additionally, using a geo-political map of international EP device manufacturers we show the steady expansion of EP technology to new countries that only recently established space heritage for their devices – South Korea, China, India, and others.

II.GEO Communication Satellites

A. Missions in the Years 1993-2016

Commercial communication satellites in GEO saw the fastest growth in the past 24 years in terms of revenue and number of satellites carrying EP systems. The increasing demand for telecommunication services, whether commercial or military, serves as an incentive for the maturation of space-proven 1-5 kW electric thrusters. Traditionally EP is used to perform station keeping maneuvers in order to maintain the spacecraft in its designated slot in the GEO belt. Most GEO satellites carrying EP systems incorporated electric thrusters solely for north-south-east-west station-keeping maneuvers. The propulsion systems consumed between 1.5kW and 4.5kW of electrical power, depending on the type of electric thruster.

In spite of years of successful use of EP for station keeping, satellite primes and operators hesitated to use EP for significant fractions of orbit raising because of the perceived high risk and financial penalties caused by the long trip times to GEO. Two missions played a key role in reducing the perceived risk of EP for orbit raising. In 2001 Artemis10 used RIT-10 ion thrusters for a major fraction of the GTO to GEO transfer to compensate for a malfunction in the launch vehicle chemical upper stage. The ion engines were fired over 18 months to reach GEO. The second key mission, Smart-1, was launched as a secondary payload to GTO and over the course of 13 months reached the Moon using a single 1.35kW Hall thruster. The combination of these missions, the successful experience

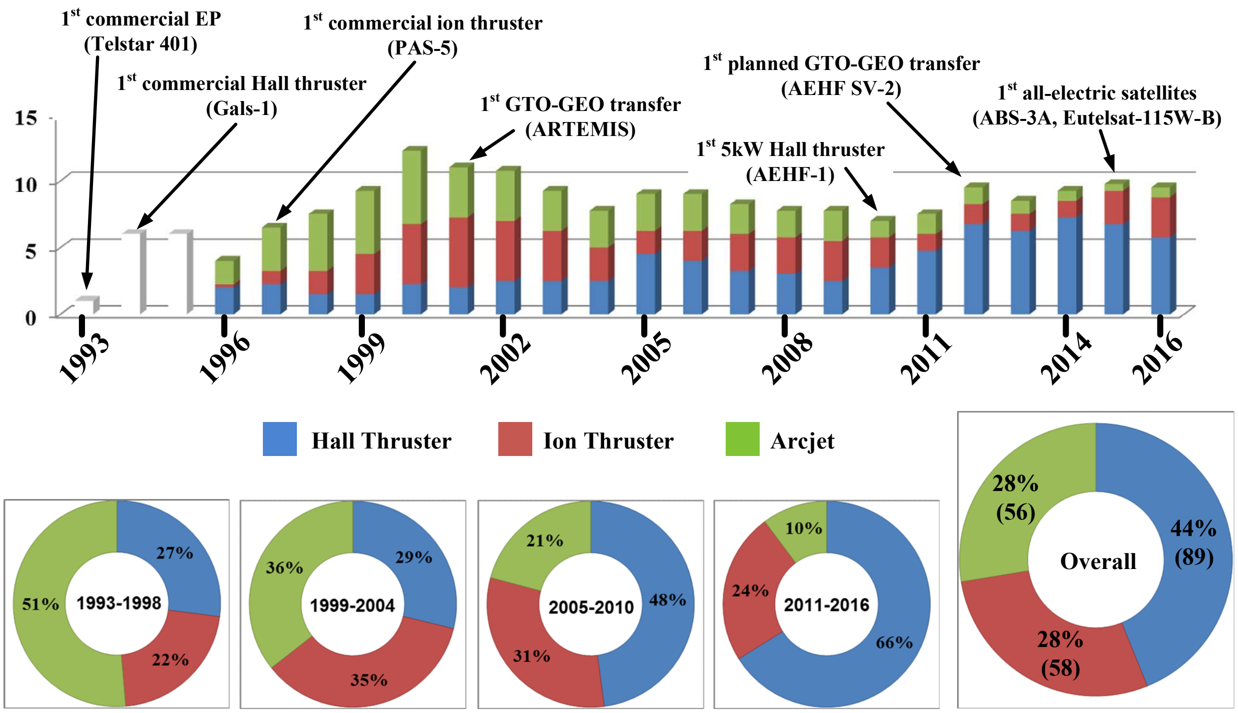
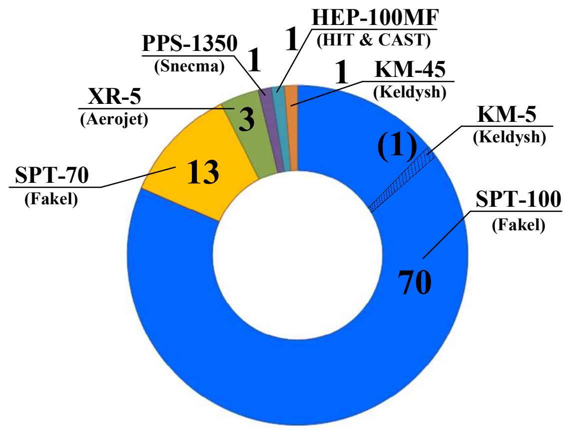


Figure 2. Top: Number of EP-based GEO satellites launched in the years 1993-2016 (4-year running average), divided into electric thruster subclasses. Bottom: Relative fraction of each electric thruster subclass for each six year period and the overall breakdown for the years 1993-2016.

with station keeping, and the development of higher power Hall thrusters led the US Air Force and Lockheed Martin to design the AEHF GEO spacecraft for EP orbit raising, with an on-board bipropellant system initially boosting the spacecraft perigee over the van Allen belts and 4.5 kW Hall thrusters operated two at a time providing the majority of the orbit raising from GTO to GEO, an approach described conceptually in Ref.11 . This orbit raising plan was complicated when AEHF Space Vehicle 1 (SV1) launched in 2010 and the on-board bipropellant system failed, forcing the use of the Hall thrusters for even more of the orbit raising than planned. Over the course of a year the Hall thrusters were successfully used to reach GEO without compromising mission life. This was followed by the launch of AEHF SV2 in 2012 and SV3 in 2013, both which performed nominally with the Hall thrusters boosting to GEO over 3 months following the initial perigee raising using the bipropellant system. Then in 2014 SPT-100 Hall thrusters were used aboard the Express-AM5 and Express-AM6 satellites to perform a planned 2,000 km orbit-raising maneuver to reach final orbit from a Proton-M launcher super-synchronous insertion orbit12. These EP orbit-raising efforts culminated in early 2015 when Boeing delivered the first all-electric satellites carrying XIPS-25 ion thrusters13. These were the first satellites without on-board chemical propulsion, and thanks to the great mass savings of using a high specific impulse propulsion system, the two satellites could be stacked and launched together, the first time ever14. In 2016, another all-electric pair of satellites was successfully launched and is operating as planned15.

Figure 2 (top) presents the number of EP-based GEO satellites launched in the years 1993-2016. A 4-year running average was used since the average order-to-launch characteristic time for GEO missions is approximately four years. Electric thruster subclasses are also presented for each year (resistojets are not included for reasons given in the introduction). The presented values include all GEO satellites that incorporated EP systems, including technological, and experimental satellites. It is assumed that technological and experimental GEO satellite missions have the same significance as commercial satellites since they often serve as precursors to future commercial or military GEO missions.

It can be seen in the figure that a roughly constant, with a slight decreasing-increasing trend, number of EP-based satellites was launched every year, with an average of about 8 satellites per year. This number is a bit higher earlier in the investigated period (the years 1999-2002) thanks to several families of satellites (AMC, Echostar and NSS) utilizing Lockheed Martin's A2100 platform[16,17] that were launched in late 1990s and early 2000s. In addition, the increase at the end of the investigated period (the years 2012-2016) is most likely due to the gained confidence in EP technology and the slow entrance of new propulsion developers into the GEO satellite market, such as the Chinese ion (LIPS-200[citation]) thruster, European Hall (PPS-1350[citation]) thruster or the American 5 kW Hall (XR-5[citation]) thruster.



HIT – Harbin Institute of Technology
CAST – China Academy of Space Technology

Figure 3. Number of GEO satellites using Hall thrusters in the years 1993-2016 (by Hall thruster type and manufacturer). Ekspress A4 carried both SPT-100 and KM-5 thrusters.

Three subclasses of electric thrusters were used for GEO station keeping and later for orbit raising maneuvers – arcjets, Hall thrusters, and gridded ion thrusters. These technologies were chosen for their power consumption, thrust, specific impulse, and lifetime. Of the three, arcjet technology was most mature at the beginning of the investigated period, making arcjet technology the most prolific at that time (Figure 2). More than 95% of the 56 GEO satellites harnessing arcjet technology used Aerojet's MR-51018 aboard Lockheed Martin's A2100 satellite platform. The first operational use of arcjets for GEO satellites in Japan was also using Aerojet's systems on the DRTS satellites [citation].

In parallel with arcjet technology, and by virtue of its higher specific impulse, ion thruster technology gained acceptance. Hughes, later acquired by Boeing, served as the leading ion thruster developer with the development of the XIPS-13 and XIPS-25 thrusters that were used on 601 and 702 satellite platforms[citation]. Of the 58 satellites incorporating ion thrusters in the investigated period, 31 satellites used the XIPS-25¸ 22 used the XIPS-13 and 5 satellites used thrusters developed and produced by other entities (European or Japanese RF ion thrusters).

Hall thruster technology migrated to the west during the 90's and in the past 20 years was increasingly used by Russian, American, and European primes. Hall thruster technology was found attractive because of its high specific impulse, compared to arcjet technology, and because it produces about double the thrust-to-power ratio relative to ion thrusters, albeit the lower mass savings. The success of utilizing Hall thrusters aboard GEO satellites made the technology the most used form of electric propulsion by the year 2016. IAs shown in Figure 3 the various types Fakel's SPT-100 Hall thruster[19,20] have dominated the Hall thruster market with 70 of 89 satellites incorporating this 1.5 kW thruster. However, in recent years new American, European, Chinese, and Indian Hall thrusters penetrated the GEO satellite propulsion market[citation], indicating on a trend shift in which a variety of different Hall thrusters will be available for future missions.

Overall, during the years 1993-2016, a total of 203 GEO satellites incorporating EP systems, excluding high power resistojets, were launched. The most used subclass to date is Hall thrusters, comprising approximately 44% of all EP types, followed by ion thrusters (28%), and arcjets (28%).

B. Future Electric Thrusters

Recent Hall thrusters such as Fakel's SPT-140D[citation] or Safran's PPS-5000[citation] produce a level of thrust significantly higher than earlier generations from Safran, making it possible to consider full electric orbit raising with an acceptable transfer duration, even for large satellites. For instance, Airbus-built Eutelsat 172B (Figure 4), the first high power satellite by Airbus to use EP for all maneuvers, is completing its orbit raising to GEO within about four months after its June 2017 launch by Ariane 5 into a GEO standard transfer orbit.

The SPT-140 finished its qualification process in 20??..... It is a ?? watt Hall thruster capable of….. The thruster is planned to be launched on board…. In the year… and perform…

The PPS-5000 finished its qualification process in 201?..... It is a ?? watt Hall thruster capable of….. The thruster is planned to be launched on board…. In the year… and perform…

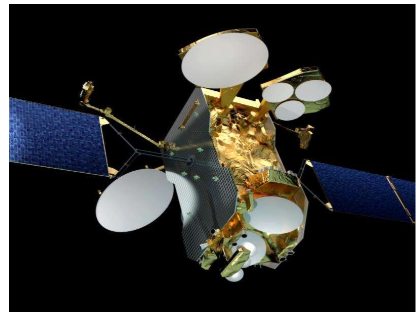


Figure 4. Eutelsat 172B impression in orbit21.

In China during the past few years electric propulsion has been developed with a specific road map22 in which ion and Hall thrusters are firstly launched on experimental LEO and GEO spacecraft. The main purpose of these technological missions is to lay the groundwork for two future commercial GEO satellite platforms to utilize EP – the DFH-5 and the all-electric DFH-4SP platforms. Both platforms will utilize the LIPS-300 ion thruster. In July 2017 the LIPS-300 ion thruster was launched aboard the Shijian-18 satellite which was lost due to launch failure23. In parallel, Harbin Institute of Technology (HIT), in cooperation with the China Academy for Space Technology (CAST), has developed, and in late 2016 flight-tested, the magnetically focused Hall thruster (HEP-100MF) which is a promising high-efficiency variation of conventional Hall thrusters.

One short paragraph on Lockheed's future platform. Maybe the new A2100 platform to use the XR-5 thruster (contract with Aerojet was signed in June 2015).

Table 1. List of electric thrusters used during 2017 or qualified to be used aboard GEO satellites.

Name	Manufacturer	Electrical Power [W]	Year of Launch (or planned launch)	TRL
SPT-140	Fakel	4,500	2017	9
KM-45 (GSAT-9?)	Keldysh			
PPS-5000	Snecma	5,000	2019???	8
LHT-300	Lanzhou Institute of Physics	3,300	2017	8

III.Low Earth Orbit (LEO) Satellites

LEO satellite platforms, weighing over 100 kg, are designed to perform a variety of missions such as Earth observation, atmosphere monitoring, rapid communication to Earth, or purely scientific missions24. To do so, different maneuver capabilities are required from the propulsion system – short periodic orbit maintenance activations, long high impulse orbit raising operation, low thrust attitude control impulse bits, or continuous operation for drag compensation. Each mission necessitates a specific propulsion system tailored to meet mission maneuverability needs. For this reason, the requirement diversity of LEO satellite propulsion systems is greater than that of GEO communication satellites. The earliest successful operational use of electric propulsion on a LEO small satellite was on the TIP/Nova small satellites, which used pulsed plasma thrusters for fine orbit control starting in the 1981. However, developments in other satellite systems and small hydrazine thrusters reduced the benefits from early electric propulsion systems and delayed further application. More recently, as EP technology has matured and mission requirements have increased, use of EP systems on LEO small satellites has been revisited.

Table 2. List of all LEO satellites using electric propulsion and weighing over 100 kg that were launched in the years 1993-2016

Name	Purpose	Launch Mass, kg	Year of Launch	Thruster Type	Thruster	Application	Comments
XY 2 (Kaituo 1A)	Technological/scientific	130	2015	HT	LHT-100 (China)	Thruster Demonstration and Evaluation	
X-37B OTV-4	Technological/scientific	5400	2015	HT	XR-5 (USA)	Thruster Demonstration and Evaluation	
Deimos-2	Earth Observation	310	2014	HT	HEPS (S. Korea)	Orbit Maintenance	
EgyptSat 2	Earth Observation	1,050	2014	HT	SPT-70 (Russia)	Orbit Insertion, Orbit Maintenance	
DubaiSat-2	Earth Observation	300	2013	HT	HEPS (S. Korea)	Orbit Maintenance	
STSAT-3	Technological/scientific	175	2013	HT	HEPS (S. Korea)	Orbit Maintenance	
Shinjian-9A	Technological/scientific	790	2012	Ion Thruster	LIPS-200 (China)	Orbit raising	
Kanopus-V 1	Earth Observation	473	2012	HT	SPT-50 (Russia)	Orbit Maintenance	
FalconSat 5	Technological/scientific	180	2010	HT	BHT-200 (USA)	Orbital Maneuvers	
STSAT-2B	Technological/scientific	100	2010	PPT	(S. Korea)	Orbit raising	Lost in launch
STSAT-2A	Technological/scientific	100	2009	PPT	(S. Korea)	Orbit raising	Lost in launch
GOCE	Technological/scientific	1,077	2009	Ion Thruster	T-5 (UK)	Drag Compensation	
TacSat 2	Technological/scientific	370	2006	HT	BHT-200 (USA)	Drag Compensation Technology Demonstration	
Monitor-E	Earth Observation	750	2005	HT	SPT-100 (Russia)		
EO-1	Technological/scientific	573	2000	PPT	I_tot~1500 kNsec (USA)	Attitude Control technology demonstration	
AO-40	Technological/scientific	397	2000	Arcjet	ATOS (Germany)	Thruster Demonstration and Evaluation	
Argos	Technological/scientific	2,720	1999	Arcjet	26kW Arcjet (USA)	Thruster Demonstration and Evaluation	
STEX	Technological/scientific	693	1999	HT	TAL-D55 (Russia)	Thruster Demonstration and Evaluation	

A key constraint on EP systems of LEO satellites is their power limitation. Unlike GEO comsats, LEO satellite platforms typically have smaller, lower power payloads, enabling the small, lightweight low power platforms. Since smaller platforms are capable of generating merely hundreds of watts, due to partial exposure to the sun (in LEO) and limited size of their solar panels, these platforms may usually accommodate low power electric propulsion systems of no more than several hundred watts25.

Given the above-described propulsion system frame-of-work four types of electric thrusters have been used in last 18 years: (1) PPTs, (2) Arcjets, (3) low power Hall thrusters, and (4) low power ion thrusters. All four types were incorporated onboard a total of 18 LEO satellites weighing over 100 kg. All 18 satellites are listed in Table 2. It is noteworthy that seven of the 18 satellites were technology demonstration missions, not operational missions, enabled by the lower cost of LEO satellites.

While the missions in 1999 and 2000 included demonstrations of arcjet, PPT and Hall thruster systems, Hall thrusters became more dominant as mission heritage was gained and newer players, such as South-Korea, developed their versions of electric thrusters[citation].

It can also be observed in the table that only two ion thrusters were launched on LEO platforms. The first is the LIPS-200, a Chinese 1kW thruster operated in LEO26 to flight-test it as preparation for future missions aboard GEO platforms27. The second thruster is the QinetiQ T5 Kaufman-type ion thruster28, was chosen for a LEO mission, that is for GOCE, where high specific impulse and low thrust throttling capability were needed to reduce propellant mass and allow for accurate continuous drag compensation29.

The relatively low number of satellites utilizing electric thrusters is mainly due to the lack of commercial incentives for LEO missions, which have also prevented the industry from developing and proving the suitable low power technology to meet LEO satellite maneuverability demands. This fact left low power thruster development in the hands of the various governments that invested their efforts to meet Earth observation needs (Figure 5).

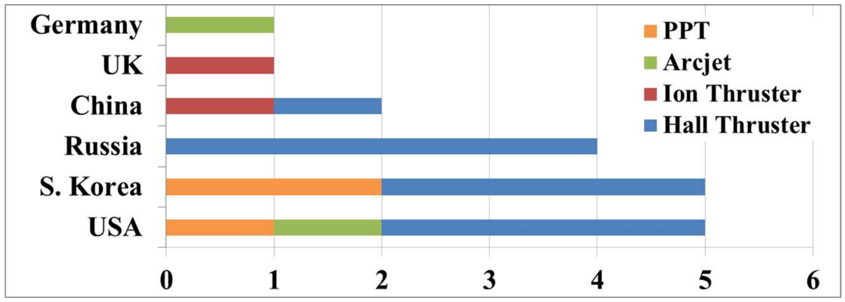


Figure 5. Number of LEO satellites incorporating electric propulsion systems (by nation and by thruster type).

Finally, because the required ΔV of LEO platforms is relatively low, for most LEO missions the advantage of using electric propulsion is usually not that significant compared to chemical propulsion.

Several factors may change today's picture and increase the usage of electric propulsion for LEO satellites:

1) Growing commercial incentives – In the past three years, there is a fast-growing commercial interest in using LEO telecommunication satellite constellations to enable low-latency internet access to large parts of the world30. These satellites, which must be positioned above an altitude of 1,000 km31, require performing an energy-costly orbit raising injection maneuver. The associated ΔV required to perform the maneuver makes high specific impulse electric thrusters an attractive option for these satellite platforms, which is why companies such as SpaceX and OneWeb are developing their own EP-based platforms32[citation on OneWeb].
2) Longer mission lifetime – As technology progresses, the average LEO satellite lifetime extends, requiring additional propellant; therefore, making high specific impulse and long-lifetime electric thrusters an attractive option.
3) Deorbit requirement – To reduce the amount of space debris, many countries require that each LEO satellite be equipped with some means of propulsion which will enable the spacecraft to maneuver into a disposal orbit. The deorbit requirement increases the overall required ΔV for the satellite platform, making electric thrusters more attractive for LEO platforms.
4) New maneuvers – Low thrust high specific impulse capability allows for a variety of maneuvers that could not be performed in the past. Altitude change, plane change and phase change33 (to enable satellite servicing or satellite re-positioning), drag compensation and full attitude control (replacing the reaction wheels) to name a few. The new potential applications open the door for new possible missions, increasing the overall requirement for LEO satellites in general and electric propulsion in particular.

IV. Planetary and Interplanetary Spacecraft

C. Missions in the Years 1993-2016

Electric propulsion stands out as an attractive choice for planetary and interplanetary missions thanks to its high specific impulse compared with other types of propulsion. Of the various electric propulsion technologies, ion thrusters possess the highest specific impulse and are able to deliver the total impulse required for these missions. For this reason, ion thrusters are the most common form of electric thrusters used for interplanetary missions34,[35]. In fact, five of the eight EP-equipped interplanetary spacecraft utilize ion thrusters as their main means of propulsion.

The electrical power consumed by the electric thrusters depends on mission needs and varies between several watts (Electrospray thrusters on Lisa-Pathfinder[citation]) to almost 5 kilowatts (SPT-140 on Fobos-Grunt19, which was lost due to launch failure), and span a total impulse range of X N-S to Y N-s depending on the mission requirements and technology capability

Figure 6 and Table 3 lists all interplanetary missions based on electric propulsion technologies. It can be observed that only eight interplanetary missions included electric propulsion in the past 20 years. The low figure is mainly due to the high risk and cost associated with interplanetary missions that led to a natural tendency for spacecraft designers to choose well-based technologies with extensive in-flight operation history, such as chemical thrusters. However, over time confidence in electric propulsion technologies grows and an increasing number of interplanetary spacecraft included electric propulsion systems, as seen in Figure 6.

It is expected that in the future an increasing number of EP-based interplanetary missions shall incorporate electric propulsion. (This section needs to be longer)

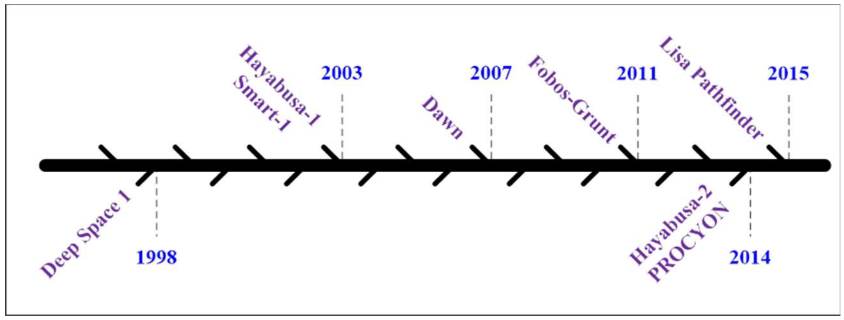


Figure 6. Interplanetary missions utilizing electric propulsion in the years 1993-2016.

Table 3. List of planetary and interplanetary missions using EP in the years 1993-2016.

Mission Name	Destination	Launch Year	Prop. Sys. wet mass, kg	EP Technology	Power, kW	Total Impulse, N-sec
Deep Space 136	Asteroid	1998	129.5	NSTAR (Ion Thruster)	0.48-1.94	2.73×10^6 (qualified)
Hayabusa-137[38]	Asteroid	2003	125	µ-10 (Ion Thruster)	0.25-0.35	1×10^6 (in space)
SMART-139	Moon	2003		PPS-1350 (HT)	0.65-1.41	1.2×10^6 (in space)
Dawn40	Protoplanets Vesta & Ceres	2007	554	NSTAR (Ion Thruster)	0.52-2.57	
Fobos-Grunt	Mars	2011		SPT-140 (HT)	4.5	
Hayabusa-238	Asteroid	2014	127	µ-10 (Ion Thruster)	0.31-0.42	1.2×10^6 (heritage)
PROCYON35	Asteroid	2014	9.5 (with cold gas system)	I-COUPS (Ion Thruster)	0.038	
Lisa Pathfinder	L-1	2015		(Electrospray)		

D. Future Missions

Due to the fact that interplanetary missions require a relatively long development and preparation period, the general spacecraft architecture of most missions for the next decade are delineated. Future known interplanetary missions incorporating electric propulsion technologies are described hereafter:

1) **BepiColombo** -. The ESA Cornerstone mission to the planet Mercury, BepiColombo41 (Figure 7), foresees for the electric propulsion options an ion propulsion system with high specific (>4000 sec) and high total impulse capability. The BepiColombo Solar Electric Propulsion Module will be propelled by a cluster of high-power (in the 2.5-4.5 kW range) gridded ion thrusters providing a maximum thrust of 143 mN each. The system architecture philosophy will maintain one complete propulsion unit (Thruster, PPUs and FCU) in cold redundant status. For the ESA technology development activities supporting the BepiColombo program, the QinetiQ T6 electron bombardment ion thruster[42] has been selected. During 3,000 hours of thruster characterization test a single and twin configuration has been investigated. Thruster characterization with one single neutralizer in twin thruster configuration and a test at high temperature has also been performed. Analysis on the lifetime capability of the thruster (ion optics and components) will provide suitable data for the improvement of the design and of the thruster reliability. A lifetime test will also take place. Mission launch is forecast in 2018.

Figure 7. Illustration of the BepiColombo spacecraft.

2) **Psyche** – Selected by NASA in January 2017 and slated for launch in 2022 as part of the latest Discovery mission competition, the Psyche spacecraft[58] (Figure 8) would investigate 16 Psyche, a large M-type asteroid orbiting the Sun at roughly 3 AU. For Psyche, ASU and JPL have partnered with Space Systems/Loral, LLC (SSL), a commercial satellite manufacturer with extensive experience developing and flying high power SEP spacecraft. The Psyche spacecraft conceptual design leverages SSL's existing product line by multiple SPT-140 Hall Effect thrusters, each of which provides a maximum thrust of approximately 250 mN. The SPT-140 thruster was flight qualified by SSL for their commerical GEO spacecraft product line in 2015, and is currently scheduled to fly on an SSL spacecraft in 2017[59]. During early concept studies, testing was conducted on the SPT-140 to extending its throttle range and lifetime to match Psyche's mission requirements[60,61]. In order to address the variation in peak power voltage (65 to 100 V) over variable distances from the Sun, the Psyche spacecraft concept design utilizes a power architecture in which discharge converters from SSL's GEO heritage product line boost solar array voltage to provide 100V regulated power to the Power Processing Unit. The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Figure 8. Artist's concept of the Psyche Spacecraft.

1) **Complete with relevant picture and citations (use the 'New Comment' option under the 'Review' tab for citations/references. I will already organize all references in the reference section).**
2) **Are there any Russian, Japanese, Chinese or Indian future missions using electric propulsion**?
3) **Near Earth Asteroid (NEA) Mission** – **Complete**

V.Small Spacecraft under 100 kg

Mini-satellites, Microsatellites43, and CubeSats44 are a rapidly growing niche in the space industry. Since 2010, the number of small satellites launched expanded by hundreds of percent to over a hundred spacecraft launched in the year 2016. Moreover, it is estimated that in the next three years this figure would increase to over 250 spacecraft per year45. Of all small satellites under 100 kg launched since the year 1993, only 13 incorporated electric thrusters. This is due to the fact that most small satellites include a basic and minimal design, usually conducted by academic institutions or space start-up companies. In many cases the mission design does not require the use of a propulsion system. Additionally, most of the propulsion devices available to CubeSats are very expensive compared to the cost of the satellite itself and are not affordable to academic institutions. Moreover, CubeSats launched from the ISS have very strict requirements that limit the use of propulsion systems46. Nevertheless, the increasing number of small satellites, new applications found for these spacecraft and the requirement to dispose of them at the end of mission raise the demand for some means of propulsion.

Propulsion systems for small satellites must meet the following requirements:

1) Volume and Mass – Small satellites are volume-limited and subject to a stringent propellant mass requirement, increasing the incentive for higher high specific impulse propulsion systems for high ΔV missions. Depending on the size of the spacecraft, the available volume for the propulsion system ranges from less than ¼U47 up to about 1U48. Accordingly, the propulsion system's wet mass is up to several hundred grams.
2) Total Impulse – The total impulse requirement is determined by the nature of the mission. Typical values range (**Add typical values of total impulse for small satellites**), generated by propulsion systems with specific impulse between 400 and 3100 seconds.
3) Low Electromagnetic interference – Due to the compactness of small satellites, all their subsystems are near one another. Any electrostatic or electromagnetic interference caused by the electric thrusters may harm on-board electronic components, thus hindering the mission.
4) Low power – One of the major limitations of electric thrusters on-board small satellites is the low available electrical power due to the limited solar panel surface area of the small spacecraft. The typical values of the available electrical power depends on the size of the spacecraft and ranges between several watt and tens of watts. In most CubeSats, of several U, the maximum power is no higher than 10 W.
5) Cost-Effective – Most CubeSat designers are either academic institutes or small organizations aiming at moderate satellite capabilities. These entities rely on low budgets and may be willing to compromise on

reliability as long as it drives down procurement costs. Additionally, the low cost of CubeSats puts a limit on the total cost of the EP system – it cannot be larger than the cost of the satellite. For these reasons electric thrusters for CubeSat should have a simple design and made of low-cost components; eventually lowering the end price of the propulsion system.

Table 4. List of all small spacecraft (under 100 kg) using electric propulsion that were launched in the years 1993-2016.

Name	Launch Mass, kg	Year of Launch	Thruster Type	Application
AOBA-VELOX 3	2.00	2016	PPT	Orbit Maintenance
AeroCube 8D	3.00	2016	Electrospray	
AeroCube 8C	3.00	2016	Electrospray	
Horyu 4 (AEGIS)	10.00	2016	VAT	Attitude Control Orbit Maintenance
BRICsat-P	1.90	2015	VAT	Attitude Control Orbit Change
AeroCube 8B	3.00	2015	Electrospray	
AeroCube 8A	3.00	2015	Electrospray	
PROCYON	67.00	2014	Ion Thruster	Deep space travel
Hodoyoshi-4	64.00	2014	Ion Thruster	
WREN	0.25	2013	PPT	
STRaND-1	3.50	2012	PPT	Attitude Control
PROITERES	15.00	2012	PPT	
FalconSat 3	50.00	2007	PPT	Attitude Control
Illinois Observing Nanosatellite (ION)	2.00	2006	VAT	

The list of small satellites launched in the years 1993-2016 is presented in Table 4. The first small satellite to utilize electric propulsion (ION) was launched in 2006 and used a Vacuum Arc Thruster (VAT). Following the first electric thruster to be used on a CubeSat three other types of very low power thrusters were incorporated – Micro Pulsed Plasma Thrusters (μPPTs), electrospray thrusters and micro ion thrusters; summing up to a total of 14 missions. The four types of electric thrusters (VAT, μPPT, electrospray and micro ion thruster) have been under development for over a decade alongside other micro-electric propulsion devices49 which were yet to be used in space but may fly in future missions.

Vacuum arc thrusters and pulsed plasma thrusters50(Figure 9) are similar technologies that create a quasi-neutral plasma discharge and do not require a neutralizer. The former uses the cathode as propellant which is ablated during each discharge. The ablated material is accelerated by means of magneto-hydrodynamics. Pulsed Plasma Thrusters rely on a discharge between two electrodes to ablate a non-conductive propellant. PTFE is the most common propellant used for PPTs, although other materials have been proposed, such as PFPE. PPTs that use PTFE have the disadvantage that due to the chemical composition of this propellant, charring can occur. This can lead to the failure of the thruster. Electrosprays are used to produce very small controlled impulse bits. These devices are difficult to manufacture and the complexity drives up the cost significantly.

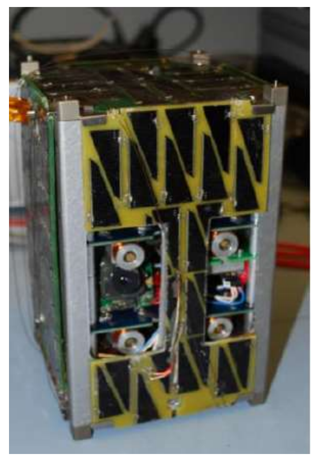


Figure 9. Fully assembled BRICSat-P, showing the side with VAT heads51.

In this subclass of EP, the first small satellite to utilized micro ion thrusters was Hodoyoshi-4 equipped with an 8.1 kg miniature ion propulsion system, denoted MIPS52. The spacecraft was launched in June 2014 and the ion thruster first operated in October 2014 where it showed a couple of successful operations during a limited visible time in LEO.

Another miniature ion thruster with the same design as MIPS was equipped on an interplanetary micro-spacecraft, PROCYON53, which was launched to an interplanetary orbit in December 2014 along-side with Hayabusa-2. The propulsion system is a unified propulsion system of a miniature ion thruster and eight xenon-cold-gas jet thrusters54. The ion thruster and cold-gas thrusters shared the same propellant (xenon) to reduce the system's dry mass to 9.96 kg, including 2.52 kg of xenon propellant. The ion thruster experienced 223 hours operations in orbit while the cold-gas thrusters managed angular momentum during one year and tested transverse acceleration several times55. It is the first small satellite equipped with a full-set propulsion: main-engine for delta-V and multiple thrusters for RCS.

An up-and-coming micro ion thruster technology is Busek's iodine-fueled BIT-3 system56, scheduled to launch on two deep space 6U CubeSat missions onboard NASA's SLS EM-1 in March 2019. BIT-3 is a unique system because it is the first flight ready EP using solid iodine as propellant, in addition to having one of the highest total impulse per unit volume, at 38kN-sec/U. Performance wise, Busek has demonstrated iodine can produce similar thrust-to-power ratio as legacy propellant xenon57; therefore, iodine will likely become a de-facto EP propellant of choice for 10-50kg MicroSats in the coming years.

(**add the advantages of electrospray thrusters. Maybe mention Accion's 'Tile'**).

(**Maybe say a few more words on the difference between the four technologies. Most importantly: associate each technology with satellite/mission applications and maneuver capabilities**)

It is interesting to note that about half of the EP-based satellites were launched in the years 2015-2016, hinting on the growth potential that micro- electric propulsion has thanks to the small satellite market growing trend. It can therefore be speculated that electric propulsion for the small satellite market will greatly expand in the upcoming years.

VI.Conclusion

TBD

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